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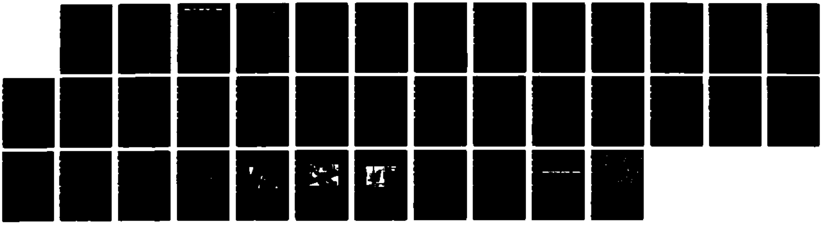

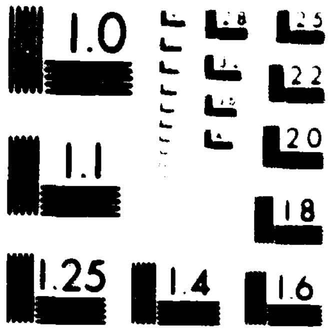
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Ship Materials Engineering Department
Research and Development

Experimental and Analytical Investigation on a Proposed Embedded Fiber Optic Displacement Sensor

by
Roger Crane
Harry Telegadas

DTRC SME-87-95 Experimental and Analytical Investigation on a Proposed Embedded

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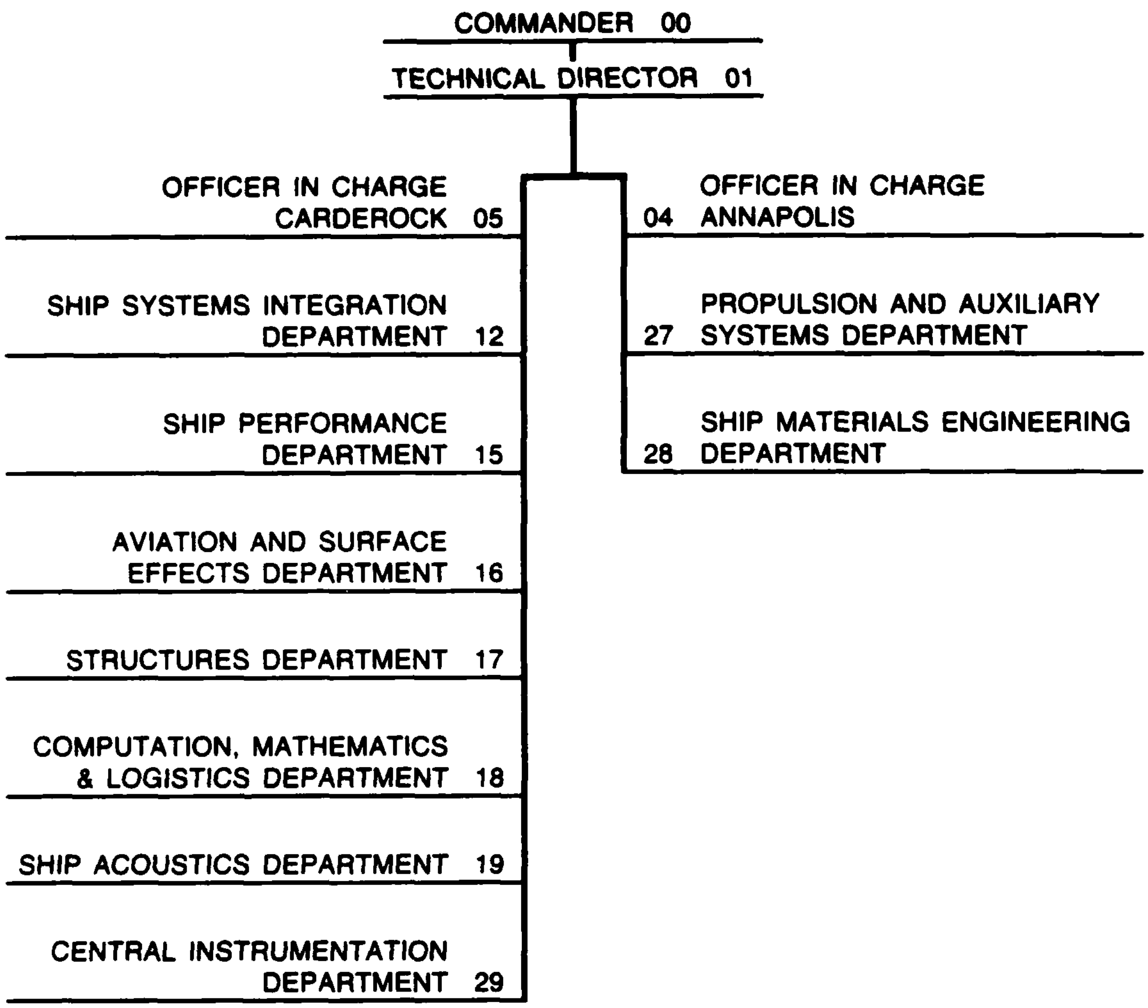

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Vibration damping measurements are currently obtained using sensors that measure beam tip displacements by determining the position of the beam cross section with time. In composites, bending-twisting couplings can occur which will result in the beam undergoing two dimensional vibration motion when subjected to a bending moment. A new monitoring technique was conceptualized and validated which utilizes embedded optical fibers as the sensors. This paper discusses the experimental validation of the concept, the physics involved in the optimization of the technique, and the areas in need of further development. The experiments have shown that two dimensional vibration can be detected using this technique. Actual displacement time information was not available for the specific test apparatus used and therefore damping loss factor information was not obtained. Further development of the data acquisition system and methodology for determination of the image center is required along with an appropriate grid xy sensor in order for the technique to be acceptable as a new technique for measuring the vibration damping loss factors for materials.

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ABBREVIATIONS

CID - Charge Injection Device
CRT - Cathode Ray Tube
FFT - Fast Fourier Transform
in. - inch
NA - numerical aperture
nm - nanometer

ABSTRACT

Vibration damping measurements are currently obtained using sensors that measure beam tip displacements by determining the position of the beam cross section with time. In composites, bending-twisting couplings can occur which will result in the beam undergoing two dimensional vibration motion when subjected to a bending moment. A new monitoring technique was conceptualized and validated which utilizes embedded optical fibers as the sensors. This paper discusses the experimental validation of the concept, the physics involved in the optimization of the technique, and the areas in need of further development. The experiments have shown that two dimensional vibration can be detected using this technique. Actual displacement time information was not available for the specific test apparatus used and therefore damping loss factor information was not obtained. Further development of the data acquisition system and methodology for determination of the image center is required along with an appropriate grid xy sensor in order for the technique to be acceptable as a new technique for measuring the vibration damping loss factors for materials.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

Damping loss factor determination for composite materials is currently conducted using a variety of sensors. The sensors are used to determine the displacement of the composite specimen during vibration as a function of time. A Fast Fourier Transform (FFT) is performed on the displacement vs. time information to obtain the frequency response of the vibrating beam in the form of an amplitude vs. frequency plot. Using this plot and the half-power band width method(1), the damping loss factor can be determined. Two of the more commonly used sensors available for determining the displacement vs. time information are the noncontact eddy current probe and the attached accelerometer. Both of these produce an electrical signal which can be related to a displacement.

There are two problems that are often overlooked when using these sensors. First, the analysis, using the equations of motion of a beam in bending, assumes certain conditions at the ends of the beam are known. Experimentally, it is assumed that the displacements are measured at the tip of the specimen. The sensors, however, can not be positioned at the end of the specimen, but are instead positioned close to the end and do not therefore measure actual tip displacements. Secondly, these sensors detect displacements, or an acceleration, at a particular cross section of the specimen. The assumption made in the data reduction is that the cross section moves uniformly with one dimensional vibratory motion, i.e. the plane sections remain plane. For metals, this assumption is valid, since the material is homogeneous and isotropic. With composite materials, this is not necessarily the case since bending-twisting couplings can arise which will result in two dimensional vibratory motion.

Composite materials can be fabricated with fibers oriented in many directions. Two generic orientations are off-axis and angle ply. In the off-axis case, the fiber orientation is all in one direction, such as 20 degrees from the loading axis. In the angle ply configuration, the fiber orientation is, for example, ($\pm$20). As a result of the fiber orientations, stress couplings can occur. These include stretching-shearing coupling, twisting-stretching coupling, bending-twisting coupling and bending-stretching coupling.

In vibration testing, the composite material is subjected to a bending moment. If the material has a laminate configuration which has either a bending-stretching or a bending-twisting coupling, the loss factor that is measured for the material is a combination of the material's loss factor as well as the loss due to the stress coupling from the particular configuration.

The configuration of a composite has been shown experimentally to effect the materials loss factor(2,3). In figure 1, Adams and Bacon(2) have determined the damping loss factor of angle ply ($\pm\theta$) and off-axis ($+\theta$) graphite/epoxy composite material. They show that the maximum in the loss factor occurs at different angles for the angle ply and off-axis sam ples. In addition, the rate at which the magnitude of the loss factor increases are significantly different in the two cases.

When the composite is subjected to a bending moment in the x-direction, a curvature results, k_{xy}, if the D inverse matrix has a D^{-1}_{16} term (figure 2). In the case of an off-axis laminate, this term exists. The magnitude of the twist is dependent on the magnitude of the D^{-1}_{16} term. Figure 3 gives the magnitude of the term as a function of angle. The maximum in the magnitude of the twist occurs at approximately 30 degrees. This corresponds to the maximum in the loss factor for the off-axis specimens, given in figure 1. This suggests that the twist which occurs in the off-axis specimens in bending may be the mechanism of a large energy dissipation.

A further result of this analytical finding is that the off-axis specimen currently is not adequate for determining the damping loss factor as a function of angle for composite materials. If the degree of twist and the resulting damping from the bending-twisting coupling can be experimentally determined, then it may be possible to use the off-axis specimen for determination of the effect of angle on loss factor.

ANALYSIS OF THE EMBEDDED FIBER OPTIC SENSOR

Several aspects of the embedded fiber optic displacement sensor need to be addressed in assessing the feasibility of utilizing the system for tip displacement measurements in cantilever beam vibration damping experiments. These include the fiber optic light spread, fiber optic image distortion, sensor scanning rate and apparent deflection.

Light Spread: When the end of an optical fiber is separated from a sensor by a finite distance, the light emerging from the fiber end spreads. This phenomena is shown schematically in figure 6.

The image that forms on the sensor is a circle, the diameter of which is given by(4)

$$D = d + 2S\tan(\theta) \qquad (1)$$

where D = image diameter
d = optical fiber core diameter
S = sensor distance from optical fiber end
θ = optical fiber's acceptance cone half-angle.

θ is related to the fiber's numerical aperture, NA, by the following equation,

$$\theta = \sin^{-1}(NA). \qquad (2)$$

For this applications, the possible range of all of the variables in equation 1 are known. The variables and its associated limits are given in table 1. Also given in table 1 are the calculated maximum and minimum image diameters using equation 1 and the range of values in this table.

The maximum tip deflection that the beam will normally be subjected for vibration damping loss factor determination will be in the range of 0.0005 to 0.005 inches. The reason that the displacements are usually kept to this minimal level is that typically, testing is conducted in air and it has been shown that aerodynamic damping can be a major contributor to the loss factor determined from the cantilever beam test when displacements become large(5). Comparing this range to the range of image diameters given in table 1, it is seen that the image diameter is at best on the same order of magnitude as the tip deflection and at worst, an order of magnitude greater. In addition, the tip deflection will decrease with time after an initial excitation if one uses the impact method for beam excitation(6). The loss factor determination is obtained from tip deflections vs. time information.

Thus, it would appear at this point that the sensitivity of the proposed system would be inadequate for accurate determination of loss factor. However, by varying the threshold level of the optical sensors, detected image size can be varied. The light that emerges from the optical fiber from a low power laser is most intense in the core region. As the light spreads, the intensity decreases radially outward from the center beam.

A conceivable sensor would be one which contains an xy array of digital switches sensitive to, and activated by, light with an adjustable threshold. The size of the switches and spacing between them would have to be small compared to the displacements expected in order to obtain accurate measurements. The image that forms on the sensor will thus be large with respect to the switches and spacing. The size of the image could be varied by adjusting the threshold of light necessary to activate the sensor or a reference point on the image can be calculated. For example, the image center could be calculated and its motion monitored. The problem then becomes whether an accurate determination of the center can be made. These considerations are in need of further testing.

Image Distortion: If the longitudinal axis of the fiber is not normal to the plane of the sensor, the above mentioned circular image can become distorted. This is shown schematically is figure 5. The image that results is an ellipse. This distortion will occur as the cantilever beam undergoes its vibratory motion. Knowing the angle of incidence of the light to the sensor and employing equation 1, the major axis of this ellipse can be calculated from simple geometry. This angle of incidence is related to the slope of the beam from the clamped end.

As the beam is subjected to a load normal to the plane of the material, it will deflect with a particular slope dependent on various material characteristics. For isotropic materials whose response is governed by simple beam theory, the relationship between the tip deflection and beam slope can be determined. For midspan loading, the slope is a linear function of tip deflection and beam length. This relationship is given by equation 3 and is shown graphically is figure 6(7).

$$\theta = \frac{6}{5}\left[\frac{\delta}{L}\right]\left[\frac{180}{\pi}\right] \qquad (3)$$

where θ = beam tip slope in degrees
δ = beam tip deflection in inches
L = beam length in inches.

The relationship between loading, deflection and slope of a composite beam is quite complicated, especially for unbalanced and/or nonsymmetric laminates. For the sake of simplicity, equation 3 is used in all subsequent calculations. Although not entirely correct, it is felt that for an order of magnitude and parametric analysis, these values are more than adequate.

The equation for the major axis of the ellipse shown in figure 5 is a complicated function of several variables. It can be derived using equation 1 and simple geometry. The result of this derivation is,

$$A = \frac{2\ d\ (\cos^2\Phi\ \cos^2\theta + \sin^2\Phi\ \sin^2\theta) + 4S\ \cos\Phi\ \cos\theta\ \sin\theta}{2\ \cos\Phi\ (\cos^2\Phi\ \cos^2\theta - \sin^2\Phi\ \sin^2\theta)} \qquad (4)$$

where A = length of the major axis of the ellipse in inches
d = distance of sensor from beam end in inches
θ = fiber's acceptance cone half-angle
Φ = beam tip slope

Defining distortion as the difference between the length of the major axis of the ellipse and diameter of the circular image from the optical fiber in its unloaded position, fig. 4, a parametric evaluation can be performed. Figures 7A-7E show the trends of this distortion as a function of each of the above variables. In each case, the distortion was calculated by holding all parameters constant except for the variable in question. The results are that the distortion increases with increasing values of the parameter with the exception of the beam length where the distortion decreases with increasing beam length.

From figure 7, a worst case situation can be determined. The expected range of values for the core diameter, beam length, sensor distance, maximum tip displacement, and numerical aperture are given in table 2. From these values, the distorted image major axis is calculated and reported in table 2. By comparing the calculated distorted image axis with the unbent image diameter given in table 1, it is seen that distortion due to the bending of the beam is negligible. Thus, for the test conditions anticipated, image distortion is not expected to be a problem.

Scanning Rate: One method used to calculate the damping loss factor of a beam requires determination of tip deflection vs. time information. An FFT is performed on the data to convert this to amplitude vs. frequency. Using the half power point method, the loss factor is then determined(8).

The critical part of this procedure is the ability to obtain information fast enough to perform an accurate FFT. The required sampling rate must be greater than at least twice the frequency of the highest harmonic to prevent aliasing errors(1). In this case, sampling rates of 10,000 to 100,000 points per second are probably necessary. This means that the entire sensor grid must be scanned and the "off/on" state of the switch stored about once every 10 - 100 microseconds. Current state of the art hardware exists which can accomplish this task.

Apparent Deflection: When a beam is subjected to a vibratory motion, its slope from its clamped end will vary. As a result of the slope change and the fact that the sensor and beam are separated, the deflection, measured from the position of the incident light on the sensor, will be "amplified" with respect to the actual tip deflection. The apparent deflection, derived from geometric considerations is given by

$$\Delta_{app} = \Delta + S\tan(\phi) \qquad (5)$$

where Δ_{app} - apparent deflection at the sensor
Δ = actual deflection of the beam tip
S = sensor distance
ϕ - slope of beam

At first, it would appear that this relationship could be used to enhance the sensitivity of the technique by increasing the distance of the beam end to the sensor. However, by recalling equation 1, the image diameter also increases with sensor distance. To determine the effect of increasing the distance of the beam end to the sensor, the ratio of the apparent deflection to the actual deflection and the ratio of the apparent deflection to the image diameter was determined and is plotted in figure 8. The graph shows that although the actual deflection is amplified, this apparent deflection is overwhelmed by the increase in image diameter. The image diameter increases with distance at a much faster rate than the apparent deflection. In fact, figure 8 shows that the most accurate data will occur at very small sensor distances. It should also be noted that the parameters in figure 8 were chosen which would results in the smallest image diameter.

EXPERIMENTAL TECHNIQUE

A new experimental method was conceptualized in order to determine the degree of twist occurring during dynamic testing for the determination of the damping loss factor of the composites(9). This new technique involves embedding optical fibers into the composite sample, through which light, via a laser, is passed. The light passing through the embedded optical fiber, impinges on a photodetector grid. This sensor consists of an x-y square array of 512 x 512 optical detectors that are contained in an area of approximately .5 x .5 in. Displacement measurements versus time are then determined with the sensor and recorded using a computer. The demonstration of the technique was carried out using the equipment and facilities at Virginia Polytechnic Institute and State University, Fiber Optic Center. The purpose of the demonstration was to determine if the vibrations of a off-axis composite cantilever beam are truly one-dimensional.

Although such an investigation might seem trivial, the successful demonstration of this concept would enable two-dimensional motion to be determined for the first time. This would further enable an explanation of the difference in the damping loss factor determined in composite materials for off-axis and angle ply laminate materials. Determination of the beam vibratory motion may help to explained the mechanisms by which energy is being dissipated through the motion that occurs when the material is subjected to a dynamic bending displacement, and would also lead to design practices to optimize this energy dissipation.

Current sensors have the previously mentioned disadvantage of averaging the displacement of a beam cross section as a function of time. In addition, these sensors determine the displacement by conver ting an electronic signal to a specific beam tip displacement. In these cases, the displacement is not made using first principles and is therefore not as precise or accurate as one which would use an actual measure of the tip displacement. In addition, theoretical determination of the loss factor assumes that the displacements being measured are at the tip of the beam. However, due to the nature of the sensor, the actual measurement is made at some finite distance from the tip of the beam.

The system demonstration, utilizing fiber optics in composites, therefore has a number of distinct advantages in both measurement sensitivity and implementation. First, the sensor itself is embedded into the material to be tested. The sensor does not significantly effect the mechanical characteristics of the composite nor does it concentrate mass at a particular location along the beam length. This can therefore be considered essentially, a noncontact sensor. Secondly, the displacements that are measured are from light that exits the end of the fiber. This means that the displacements measured are actually tip displacements, something that has yet to be measured in the cantilever beam experiment. Thirdly, by positioning two or more optical fibers into the composite, vibratory motion of one beam position relative to another can be determined which will show whether the vibration is truly one dimensional or two dimensional. This last aspect is by far the most significant.

The material used in the experimental investigation was T-300/5208 unidirectional graphite/epoxy. Panels were fabricated with the configuration $(20_8/0/20_8)$ and $[(+20/-20)_4/0/(-20/+20)_4)$, representing an off-axis and angle ply material respectively. The optical fiber used was a single mode optical fiber, with a wavelength of 1300 nm, having a core diameter of 9 micron made by Owens Corning (material designation SDSD360726AA, 218449-10, 860202). The optical fiber was placed in the 0 degree ply so that fiber distortion will be at a minimum. There was some distortion of the graphite fibers in the immediate area of the optical fibers as shown by the photomicrograph (fig 9). To alleviate this distortion, two plies of prepreg should have been used instead of only one. The material was cured using the manufacturers cure cycle. The optical fiber was of such a length such that it was coincident with the edge of the material on one end and extended approximately 3 inches out of the beam on the other end.

In order to propagate light into the specimen, splices were made with the same type of optical fiber. The apparatus used to perform the splice is shown in figure 10. After splicing the new optical fiber onto the one in the composite, the specimen was placed into a clamping device to hold it in place, obtaining a cantilever beam configuration. Light was then propagated through the optical fiber using a 5 milliwatt Helium-Neon laser. The laser is focused through a lens to the optical fiber. The optical fiber is held in place by a clamp which has a horizontal and vertical positioning capability. This is adjusted until the optical fiber has light passing through it in the form of a 4-lobe pattern. This pattern is obtained since a single mode fiber is used and the maximum intensity is obtained when the 4-lobe pattern is seen. The light exiting the fiber at the beam end was visible to the unaided eye, as shown in figure 11. It should be noted that the 4-lobe pattern is not visible in figure 11.

The sensing system was a General Electric solid state video/digital camera, Model TN2500 consisting of a Charge Injection Device(CID) imaging array sensor. The CID consists of a two dimensional array of coupled metal-oxide silicon capacitors which collect and store the photo generated charge. This signal is then dumped to an Optomation II Electron Vision System, model PN-2304 for signal interrogation. This pattern is visualized on the CRT via the Optomation II system. The signal can then be optimized by varying the threshold and noise levels until a minimum area is obtained on the CRT.

With the equipment set-up, the composite beam is set into vibration by impacting it near the clamped end. The light incident on the sensor is then processed and the light motion displayed on the CRT. For the demonstration, the twist was visually detected on the CRT. However, due to the inability to store the information, no quantitative data was obtained. However, similar instrumentation can be configured to accurately determine displacement/time information for the determination of the damping loss factor.

CONCLUSIONS

The use of embedded optical fibers as a sensor for measuring tip displacements in the determination of composite material damping loss factor is a useful idea. This technique has the potential for determining the beam tip displacements using first principles. In addition, two-dimensional motion can be determined for the purpose of identifying loss mechanisms in composite materials. The actual motion of the beam end was able to be determined qualitatively while the beam was subjected to vibratory motion. In order to obtain quantitative displacement vs. time information, a very fine grid xy optical sensor along with a high speed data acquisition system is required. The accuracy of the technique will depend on the ability to calculate and measure small displacements of large area images. Additional testing is necessary before this accuracy can be assessed. The ability to acquire and store the displacement information from a xy grid sensor is well within the current capability of existing hardware.

Image distortion due to the fiber bending, although initially thought to be a concern, will not be a problem as long as care is taken to initially align the specimen and the xy grid sensor.

Finally, from the analysis of the system, it was shown that the distance between the beam and sensor should be made as small as possible in order to minimize light spread, and thus the image diameter projected onto the xy grid sensor. If this image becomes too large, it is conceivable that the actual motion could be undetectable with respect to this image.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Dr. R. Claus of Virginia Polytechnic Institute and State University(VPI) for the use of his equipment and facilities in the Fiber Optic Research Center. They would also like to thank K. Murphy of VPI for his help in instrumentation for the experimental setup. Finally, the authors would like to thank Dr. D. Moran for his financial support of this effort.

PARAMETER	EXPECTED RANGE
Core diameter, d Sensor Distance, S Numerical Aperture, NA	5 - 1000 0.0005 - 0.002 in. 0.2 - 0.55
Image Diameter, D (calculated value)	0.0004 - 0.04164

Table 1. Range of values for the core diameter, sensor diameter, and numerical aperture used to determine the image diameter from on optical fiber onto an xy photodetector grid.

PARAMETER	EXPECTED RANGE
Core diameter, d Beam Length, L Sensor Distance, S Max. Tip Displacement, Δ Numerical Aperture, NA	5 - 1000 6 - 25 in. 0.0005 - 0.002 in. 0.0005 - 0.005 in. 0.2 - 0.55
Distorted Image Axis, A (calculated value)	0.0004 - 0.04164

Table 2. Range of values for core diameter, beam length, sensor distance, maximum tip displacement, and numerical aperture used to determine the major axis of a distorted optical image from a beam tip displacement.

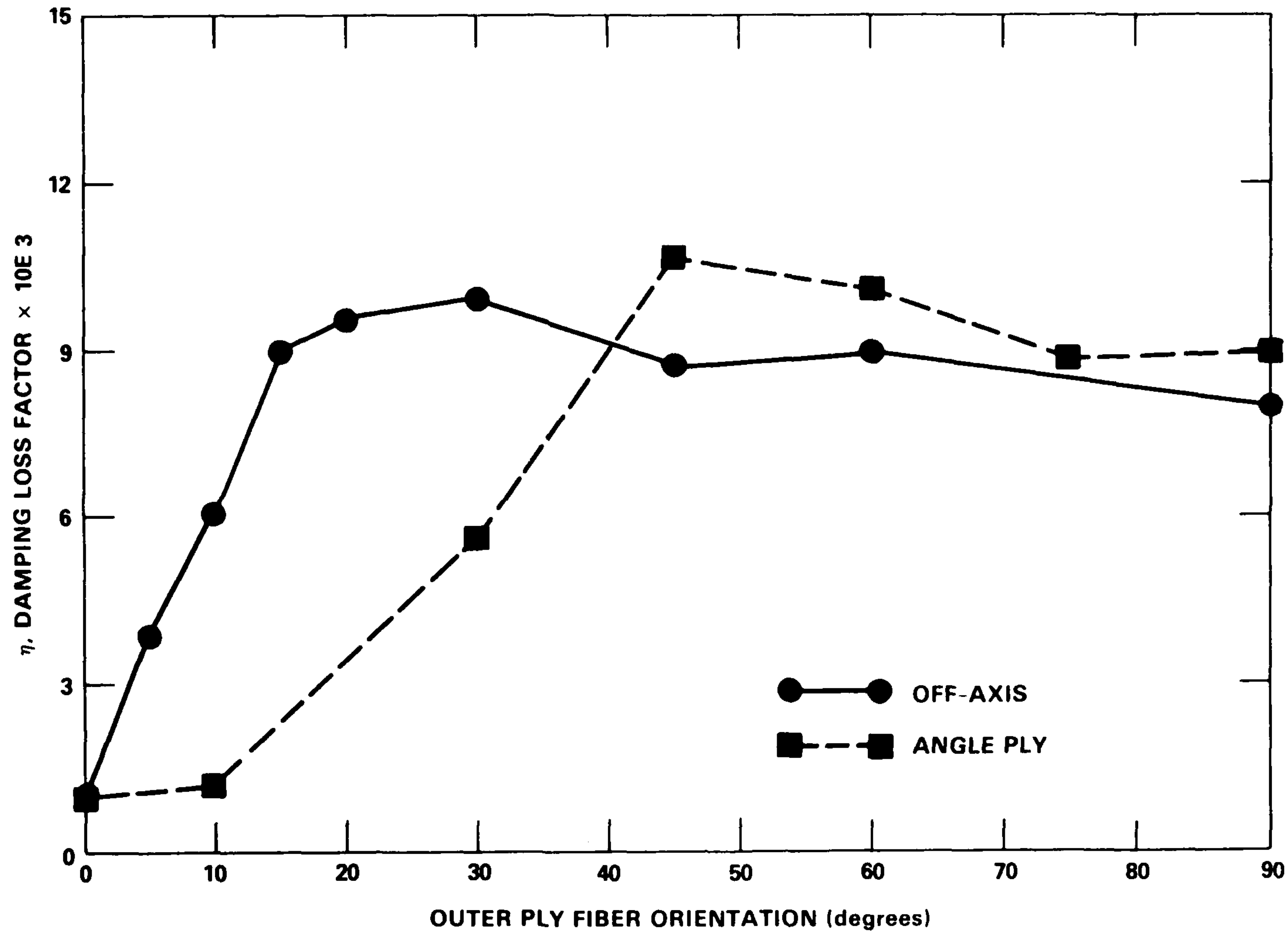

Fig. 1. Damping loss factor versus fiber orientation of off-axis and angle ply graphite epoxy (after Adams and Bacon (2)).

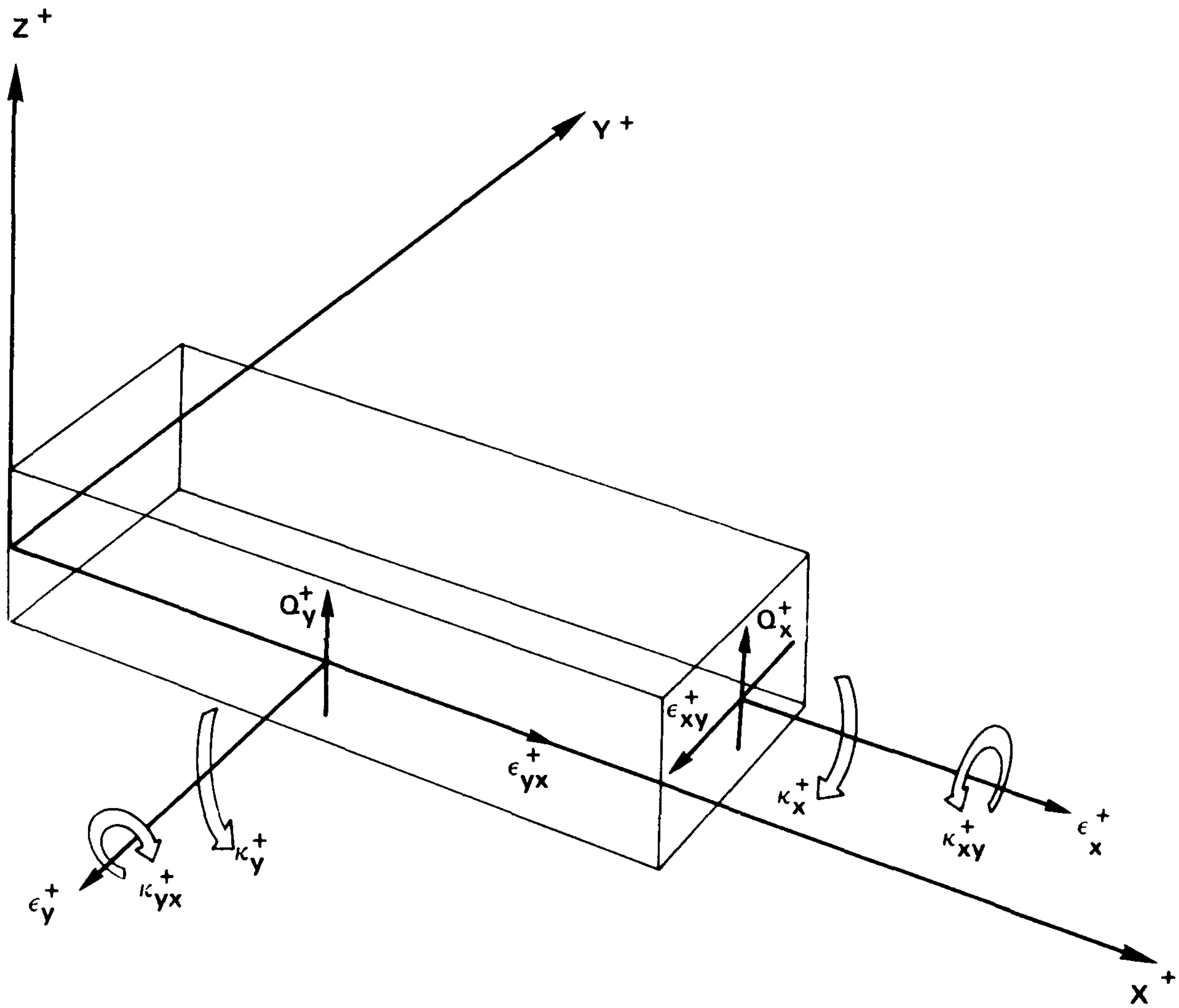

Fig. 2. Schematic of a beam subjected to bending in the x-direction showing resultant moments and curvatures.

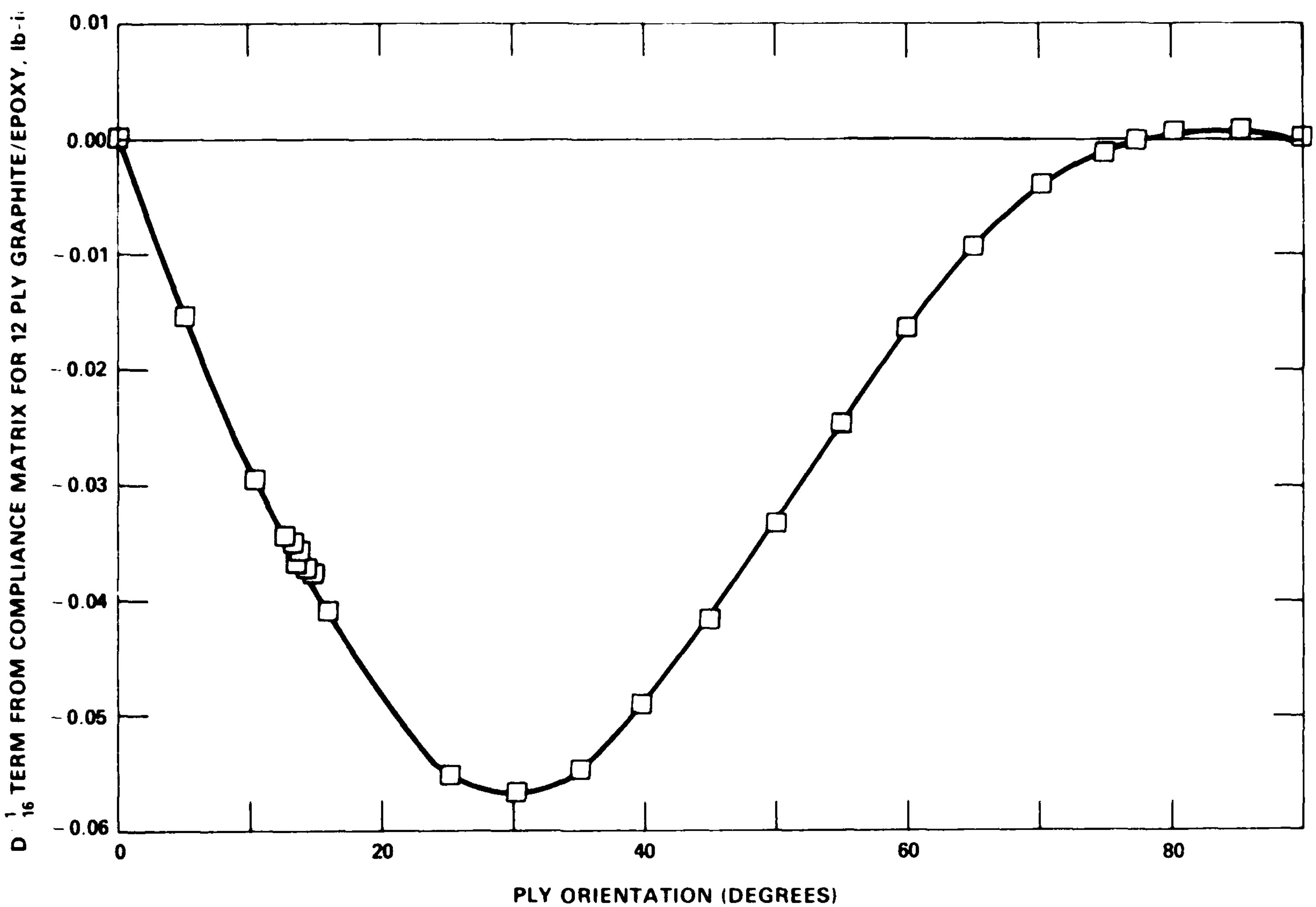

Fig. 3. Magnitude of the bending-twisting coupling term, D^{-1}_{16}, as a function of outer fiber orientation for a 12 ply graphite/epoxy off-axis laminate.

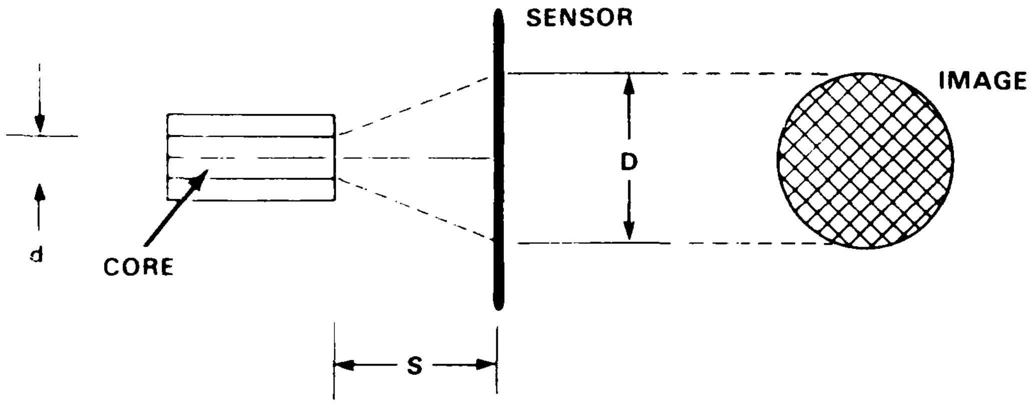

Fig. 4. Schematic of laser light exiting embedded optical fiber showing light spread as a function of distance from the xy grid sensor.

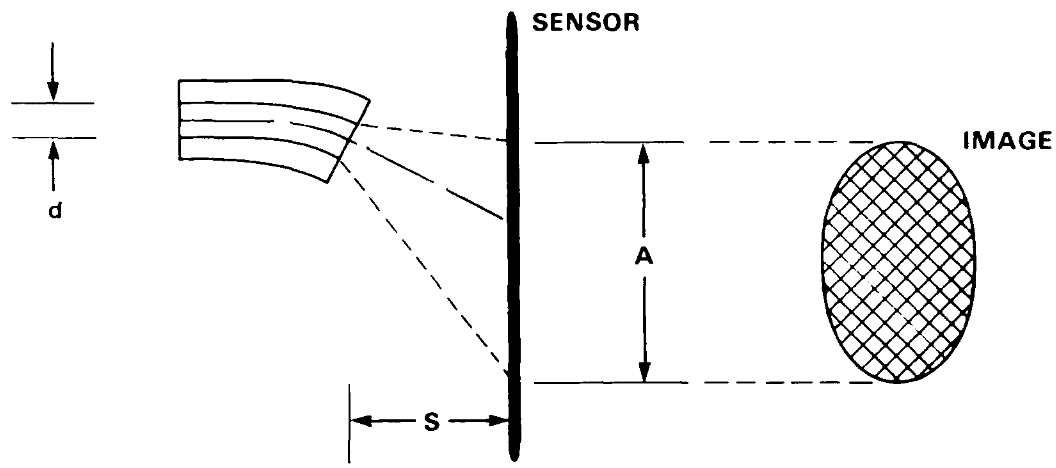

Fig. 5. Schematic of the laser light exiting the embedded optical fiber of a beam in bending showing the distortion of the light incident on the xy grid sensor.

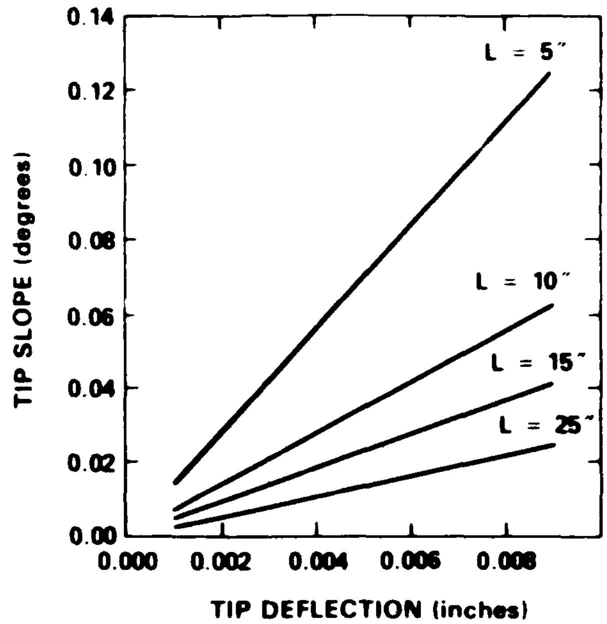

Fig. 6. Graph of the relationship between the tip slope and tip deflection for a mid-span loaded cantilever beam of different lengths, L, computed from equation 3.

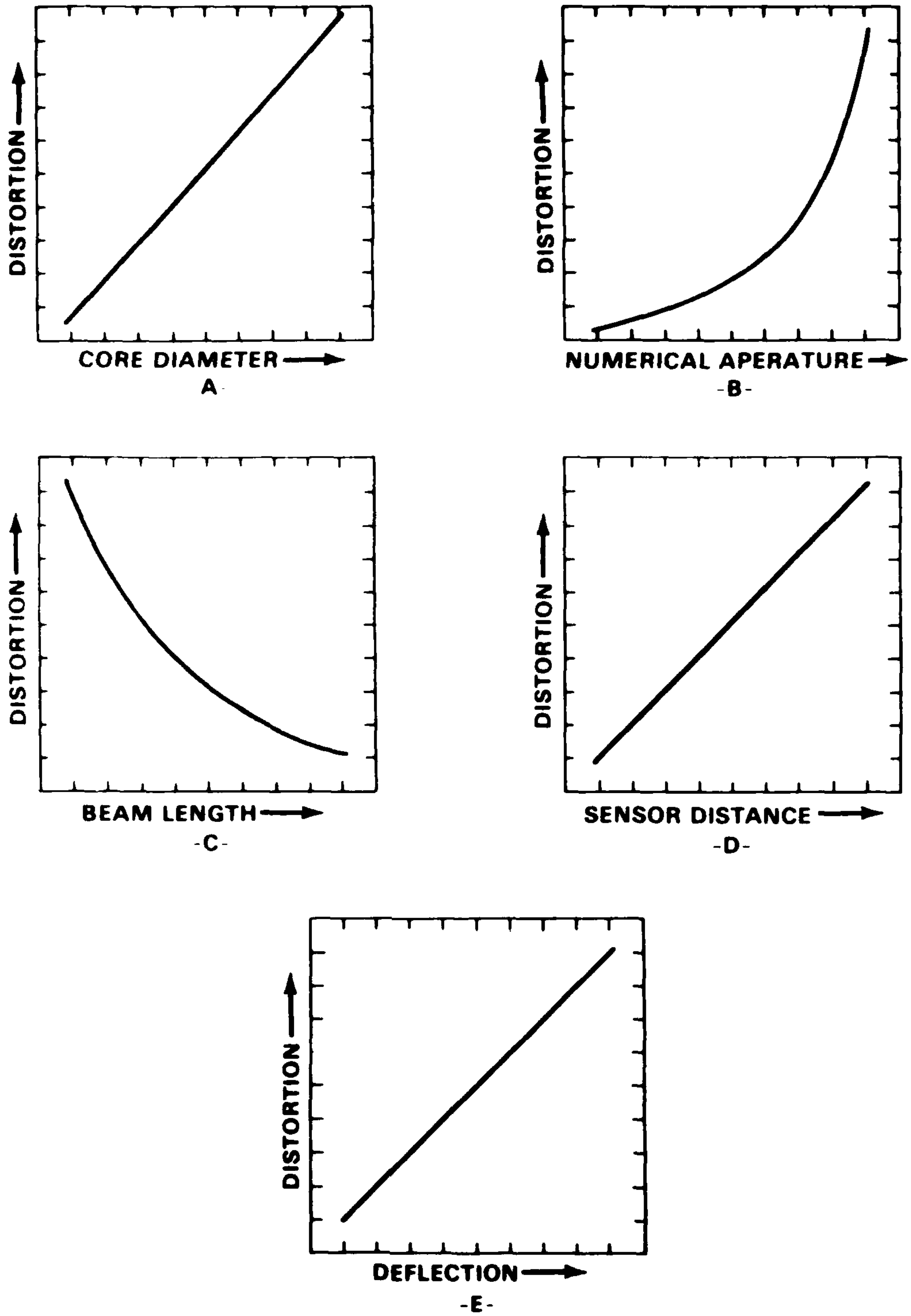

Fig. 7. Graphical representation of the trends of image distortion as a function of core diameter, numerical aperature, beam length, sensor distance, and deflection computed using equation 4.

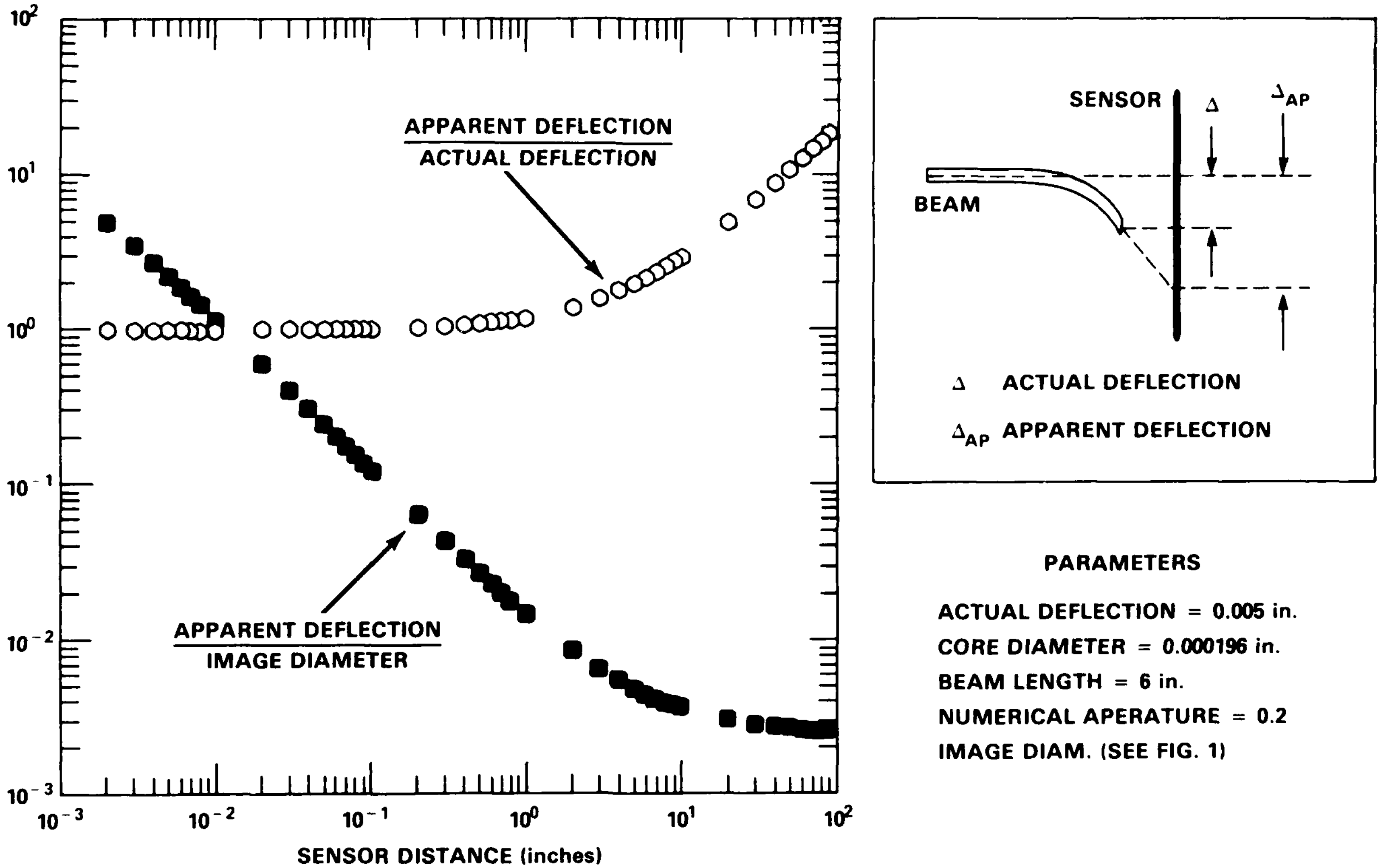

Fig. 8. Apparent deflection and image diameter as a function of xy grid sensor distance normalized as the ratios of apparent deflection to actual deflection and apparent deflection to image diameter.

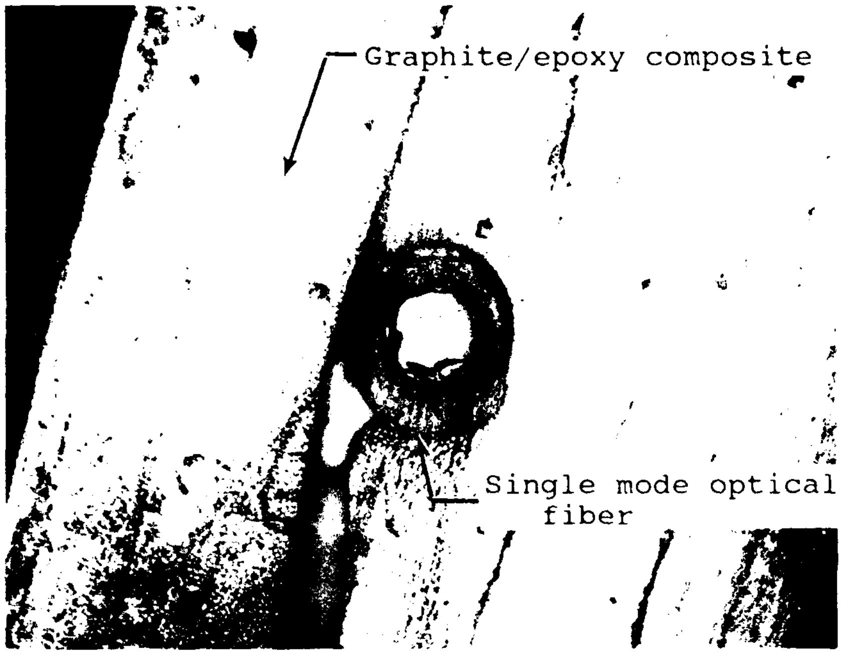

Fig. 9. Photomicrograph of a graphite/epoxy composite 9 ply (20_4/0/20_4) laminate with embedded optical fiber, center, in the 0 degree ply showing distortion to of graphite fibers around the optical fiber.

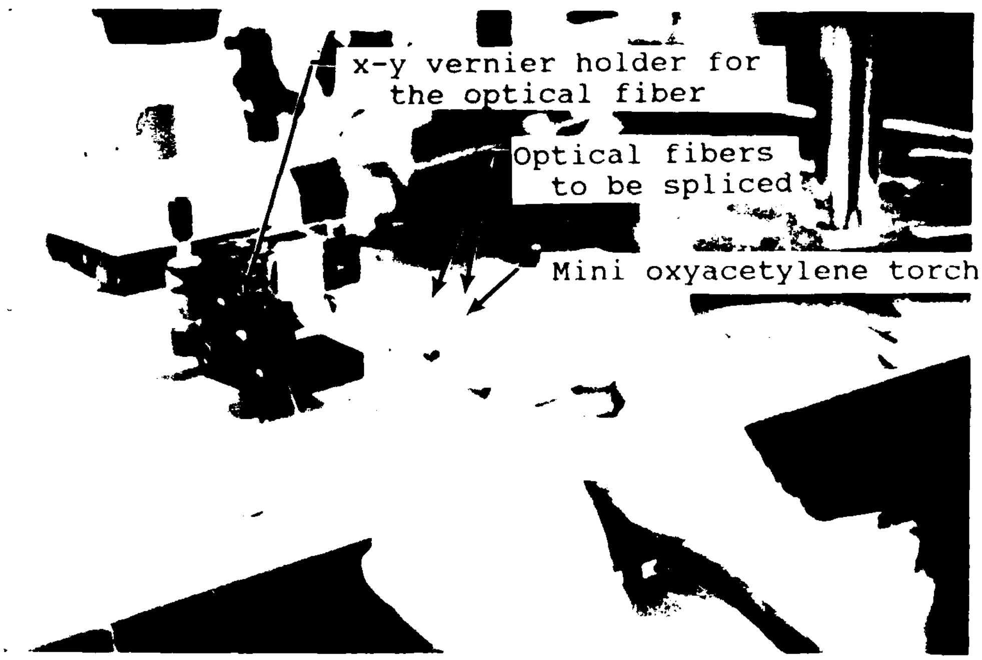

Fig. 10. Apparatus used to splice fiber optic cable to the optical fiber embedded in the composite.

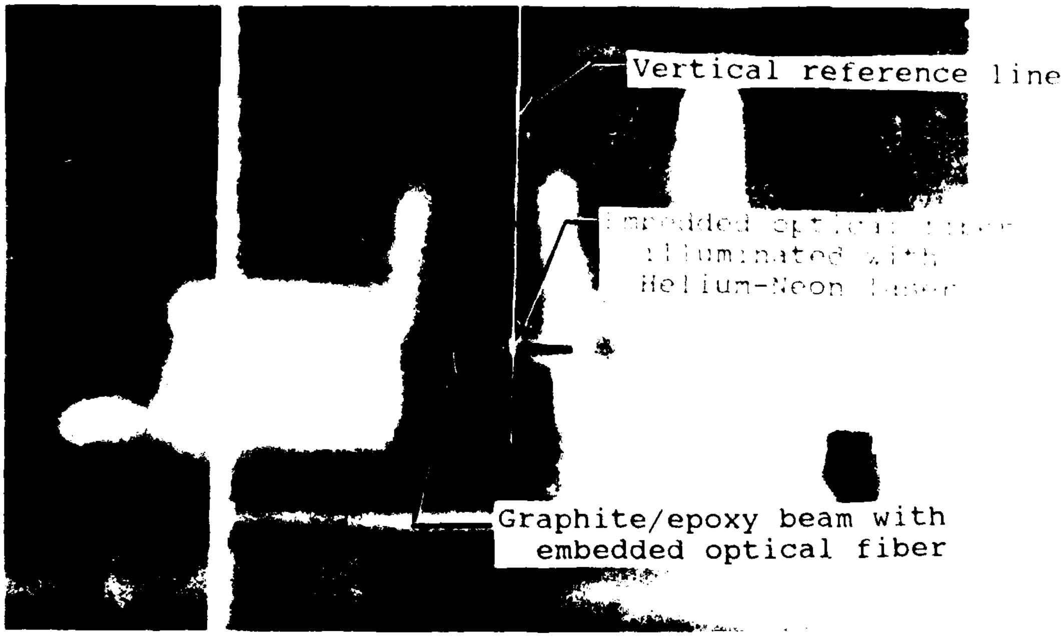

Fig. 11. Example of the laser light as seen by the unaided eye exiting the embedded optical fiber.

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